# Can a snow structure model estimate snow characteristics relevant to reindeer husbandry?

**Sirpa Rasmus[1,2], Jouko Kumpula[3] & Jukka Siitari[3]**

[1] Department of Biological and Environmental Sciences, P.O. Box 35 (Survontie 9), 40014 University of Jyväskylä, Finland (Corresponding author: sirpa.rasmus@jyu.fi).

[2] Finnish Game and Fisheries Research Institute, Jyväskylä Unit, Survontie 9, 40500 Jyväskylä, Finland.

[3] Finnish Game and Fisheries Research Institute, Reindeer Research Unit, Toivoniementie 246, 99910 Kaamanen, Finland.

*Abstract*: Snow affects foraging conditions of reindeer *e.g.* by increasing the energy expenditures for moving and digging work or, in contrast, by making access of arboreal lichen easier. Still the studies concentrating on the role of the snow pack structure on reindeer population dynamics and reindeer management are few. We aim to find out which of the snow characteristics are relevant for reindeer in the northern boreal zone according to the experiences of reindeer herders and is this relevance seen also in reproduction rate of reindeer in this area. We also aim to validate the ability of the snow model SNOWPACK to reliably estimate the relevant snow structure characteristics. We combined meteorological observations, snow structure simulations by the model SNOWPACK and annual reports by reindeer herders during winters 1972-2010 in the Muonio reindeer herding district, northern Finland. Deep snow cover and late snow melt were the most common unfavorable conditions reported. Problematic conditions related to snow structure were icy snow and ground ice or unfrozen ground below the snow, leading to mold growth on ground vegetation. Calf production percentage was negatively correlated to the measured annual snow depth and length of the snow cover time and to the simulated snow density. Winters with icy snow could be distinguished in three out of four reported cases by SNOWPACK simulations and we could detect reliably winters with conditions favorable for mold growth. Both snow amount and also quality affects the reindeer herding and reindeer reproduction rate in northern Finland. Model SNOWPACK can relatively reliably estimate the relevant structural properties of snow. Use of snow structure models could give valuable information about grazing conditions, especially when estimating the possible effects of warming winters on reindeer populations and reindeer husbandry. Similar effects will be experienced also by other arctic and boreal species.

**Key words:** calf production; reindeer; *Rangifer tarandus tarandus*; snow; snow structure; snow modeling.

**Rangifer,** 34, (1), 2014: 37-56

## Introduction

Semi-domesticated reindeer *(Rangifer tarandus tarandus)* in northern Finland live in an environment where continuously changing weather and foraging conditions significantly affect populations. In particular, reindeer herds must forage for food beneath the snow for six (southern herds) to eight (northern herds) months a year (Solantie *et al.,* 1996), with especially juvenile survival highly dependent on adequate winter forage (Holleman *et al.,* 1979). This in turn is affected both by the amount of the main winter forage, (reindeer lichens *Cladina* spp.), and also by the snow conditions on pastures (Skogland, 1978; Helle & Tarvainen, 1984; Kumpula, 2001). Both reindeer and its northern American relative, caribou *(Rangifer tarandus),* are morphologically and behaviorally adapted to Arctic ecosystems (Telfer & Kensall, 1984). Reindeer herders acknowledge the effects of weather and snow conditions on well-being of their herds, and husbandry has always been relatively adaptable to what comes to intra- and inter-annual variations in grazing conditions (Tyler *et al.,* 2007; Roturier & Roue, 2009; Riseth *et al.,* 2010; Vuojala-Magga *et al.,* 2011). Despite this, the deep snow cover and late snow melt in spring can cause high winter mortality (Adamczewski *et al.,* 1988; Kumpula & Colpaert, 2003; Helle & Kojola, 2008) and low calf production (Adams & Dale 1998; Post & Stenseth, 1999; Aanes *et al.,* 2000; Kumpula, 2001) of both caribou and reindeer.

In addition to amount of snow, the structural properties of snow are also important. The energy required for digging effort is greater with increasing snow density and hardness (Fancy & White, 1985; Kumpula *et al.,* 2004). Extensive ground ice (due to thawing-freezing at the snow-ground interface) has been observed to decrease the reproduction rates of Svalbard reindeer *(Rangifer tarandus platyrhynchus)* population (Hansen *et al.,* 2011) or even cause population crashes (Helle, 1980; Kohler & Aanes, 2004). In addition, the number of warm days (mean T > 0 °C) during early winter or the winter time rain events, which is assumed to lead to dense or icy snow cover have been shown to decrease the calf production and winter survival of reindeer (Lee *et al.,* 2000; Solberg *et al.,* 2001; Kumpula & Colpaert, 2003; Helle & Kojola, 2008). Damages to reindeer by predation are partly connected to snow conditions.

Majority of previous research has been based on measurements on snow depth and meteorological observations that have daily or rougher time scales. It is difficult to identify winters with icy snow cover using this kind of observations only (Helle & Kojola, 2008; Vikhamar-Schuler *et al.,* 2013). In Vikhamar-Schuler *et al.* (2013), a snow structure model SNOWPACK was successfully used to simulate the evolution of the snow cover, especially high-density layers, during years 1956-2010 in Kautokeino (Guovdageaidnu), Northern Norway.

SNOWPACK (Bartelt & Lehning, 2002; Lehning *et al.,* 2002a and 2002b) is a widely used model for describing the development of snow mass and energy balance during the winter. It is one of the few existing snow structure models and enables to estimate the layered structure within the snow cover and physical properties (*e.g.* density, hardness, grain size, grain type and bonding between the grains) of the layers. In this work we used combination of detailed meteorological information, snow structure simulations by the model SNOWPACK and the annually made reindeer herders' reports to create a comprehensive view on snow conditions in a selected reindeer herding district in Muonio, northern Finland.

Due to an intensive management system relatively reliable estimates on annual mortality and productivity of Scandinavian reindeer population are available. Also winter conditions, including difficult snow condition, are annually reported by reindeer herders. Unfavourable snow and weather conditions affect in a similar way to other northern ungulates, and more broadly, to several arctic and boreal species. The global mean temperature is predicted to increase by 1.4 – 6.4 °C by the end of the year 2100 (IPCC, 2007). This warming will most likely be most extreme during winters in north-eastern Europe, and precipitation (consisting of rain on snow during warm winters) is expected to increase. These changes will alter the amount and structure of snow cover, as well as in the length of the snow season, in many locations (Venäläinen *et al.,* 2001; Räisänen, *et al.,* 2003; ACIA, 2004; Rasmus *et al.,* 2004; Kellomäki *et al.,* 2010). Used together with climate model output data, SNOWPACK can work as a tool in climate impact studies. Therefore, it is important to validate this modelling tool in present day conditions and to examine its development needs.

We aim to answer the following questions:

• Which of the snow characteristics are relevant for reindeer herding in northern boreal zone according to the experiences of reindeer herders?
• Is this relevance seen also in reproduction rate of reindeer in this area?
• Is it possible to use the SNOWPACK model to reliably estimate the relevant snow structure characteristics within the study area?
• Does a snow model add information on snow and foraging conditions by reindeer compared to the conventional meteorological observations?

## Materials and methods

*Study area*

The Muonio reindeer herding district (2670 km$^2$) is located in the northern boreal zone representing typical herding districts in middle parts of Finnish Lapland (Fig. 1). Snow conditions are rather homogenous through the district. Reindeer are mainly grazed on the natural pastures in Muonio, even though supplementary winter feeding has gradually increased. According to the reindeer pasture inventory conducted during 2005–2008, 27.5% of the land area is covered by ground lichen pastures, 38.7% by mature and old coniferous forests with arboreal lichen, 20.1% by dwarf shrub and graminoid vegetation and 27.5% by mires (Kumpula *et al.,* 2009). Only small fraction of the land area is high elevation (>300 m.a.s.l), tundra vegetation. Ground lichen pastures in the Muonio herding district are mostly heavily grazed (lichen biomass < 300 kg ha$^{-1}$) although the lichen biomass is higher in a winter range than in a summer range area (Kumpula *et al.,* 2009). Arboreal lichen is found most abundantly in the old growth pine and spruce forests. Intensive land use forms in the area are forest harvesting in commercial forest area, and tourism in more local fell areas. The largest allowed number of reindeer within the district during winter is 6000; the mean number of reindeer has been 5579±419 during years 2000-2007.

*Historical records and reindeer data*

Reindeer herders' observations and experiences of winters were collected from the annual management reports during winters 1972/1973-2009/2010. Additionally, reindeer census data from the Muonio district consisting of the numbers of reindeer counted during the annual round-ups in the autumn/early winter slaughter season during the period 1972-2010 was used. Annual calf production percent in the slaughter season (autumn/early winter) after each winter was produced using information on number of calves per 100 female reindeer (calf production percentage, CPP) (data provided by Reindeer Herders' Association).

*Meteorological data*

A 37-year time series of winter weather conditions (1972-2010, except winter 1982/1983; from 1 October to 30 April for each winter) was available from a synoptic observation station in Muonio, operated by Finnish Meteorological Institute (Fig. 1). The following weather parameters were obtained: air temperature (°C), relative humidity (%), wind velocity (m s$^{-1}$) and wind direction (°), all observed from 2 meter height above the ground level. In addition, daily precipitation (mm) and snow depth values (m) were available from the station.

Annual mean temperature measured in the Muonio meteorological station was -1.4 °C during years 1971-2000, and annual precipitation 484 mm. Mean annual maximum snow depth during the period was 81 cm, with permanent snow cover usually formed after mid-October and with melting during May. Maximum snow depth is normally measured in March. (Drebs *et al.,* 2002)

We assume that weather conditions observed at the Muonio FMI station represent relatively well the general conditions of the whole reindeer herding district, and that the between-year variability observed at the Muonio station can be used as an estimate of the between-year variability on a larger area around the station.

*The SNOWPACK model*

The meteorological observations were used to run the SNOWPACK-model. SNOWPACK is a one dimensional model for snowpack mass and energy balance, developed by the Swiss Federal Institute for Snow and Avalanche Research (SLF). A complete description of the model can be found in Bartelt and Lehning (2002) and Lehning *et al.* (2002a; 2002b).

As a physically based model, SNOWPACK has been used in several applications, *e.g.* in avalanche forecasting (Lehning & Fierz, 2008) and as a part of watershed scale hydrological modeling (Lehning *et al.,* 2006). SNOWPACK can estimate the evolution of the layered structure in the snow cover and the physical properties of these layers (grain size, grain form and bonding between the grains, temperature, density and hardness of snow, fractions of ice, liquid water and air volume in snow). It has been used together with a regional climate model by inputting the climate model output data when future changes in snow cover in open area were evaluated during a 100 year time scale in the selected locations in Finland (Rasmus *et al.,* 2004) and more recently when future snow cover and its runoff in the Alps were simulated (Bavay *et al.,* 2009). The ability of the model to simulate the snow mass balance and snow structural properties has been validated in several climate conditions (Lehning *et al.,* 1998; Lundy *et al.,* 2001; Rasmus *et al.,* 2007) and it has proven to be reliable, especially in open areas. In snow structure simulations, snow temperature and density had highest correlations with observations (r=0.90 and 0.85, respectively) and grain size and type lower (r=0.30; contingency coefficient C=0.71) (Lundy *et al.,* 2001).

SNOWPACK uses air temperature, relative humidity, wind velocity and wind direction, and incoming shortwave and longwave radiation with 0.5-6 hour temporal resolution as input data. Depending on data and the aim of the simulations, either observed snow depth or precipitation can be used in the mass balance calculations of the model. Use of snow depth is justified when the data is easily available and when it is more important to simulate the snow layer properties most reliably, and in the open areas. However, precipitation data is still needed to correctly simulate the rain events which lead to icy layer formation in the snow cover.

*Model simulations on snow structure evolution*

The SNOWPACK-model was used to produce a 37-year time series on the annual evolution of snow structure on the basis of the used weather input data. Recently a canopy module has been added to the SNOWPACK model, which allows simulations also below the forest canopies (Lehning *et al.,* 2006). The canopy radiation transmission sub-model has been calibrated and evaluated by Stähli *et al.* (2009), but the ability of SNOWPACK to correctly simulate the snow structure below the canopies has yet to be validated. Additionally, the energy and mass balance calculations below the canopies are sensitive to correct estimates of forest parameters (forest height, LAI and sky view fraction; Rasmus *et al.,* 2012). For these reasons we decided to run our simulations in open area conditions only as meteorological input data was only available for open areas.

Temperature, humidity and wind data were obtained from the Muonio FMI station with a three hours resolution. Incoming shortwave radiation (W $m^{-2}$) was available from the Sodankylä FMI station (approximately 170 km away) with the same temporal resolution. Incoming longwave radiation (W $m^{-2}$) was estimated using the difference between potential and observed incoming shortwave radiation, air temperature and relative humidity in each time step (method described in Konzelmann *et al.,* 1994). Daily snow depth observations from the Muonio FMI station were used as a given parameter in simulations, because it is assumed that more exact the snow depth, the better the quality of the structure simulations.

As a bottom boundary condition there is a standard soil assumed (Bartelt & Lehning, 2002) as well as a prescribed temperature profile in the beginning of the runs. Simulations were started on 1 October and finished on 30 April for each winter. Model output included time series for the mass and energy balance components in the snow cover, as well as graphical and numerical time series of the snow structure.

*Validation of the snow density simulations*

In this study the model SNOWPACK was used to simulate the snow structure, not depth or duration of the snow cover. Grain type and bonding between the grains largely determine the density of the snow, so density simulations are suitable for testing the performance of the model.

For the validation of the snow density simulations made by SNOWPACK, we used the monthly mean snow density values measured in four permanent snow survey lines located around the Muonio weather station (Fig. 1). These long-term snow survey lines are operated by Finnish Environmental Institute, SYKE. Lines are four kilometres long with 80 snow depth and eight to ten snow density measurements, designed to include the typical terrain and biotypes (open areas, forest openings, bogs and different forest types) of the region. (Perälä & Reuna, 1990)

Table 1. Parameters listed from meteorological observations and from simulation outputs in each of the study winters. Snow density above a 350 kg $m^{-3}$ threshold was considered as icy and problematic for reindeer grazing (Vikhamar-Schuler *et al.,* 2013).

| *Parameter* | *Unit* |
|---|---|
| *From meteorological observations:* | |
| Mean snow depth | m |
| Maximum snow depth | m |
| Snow cover formation | date |
| Snow melt | date |
| Snow cover duration | days |
| *From simulation outputs:* | |
| Ground surface temperature on snow formation date | °C |
| Mean ground surface temperature | °C |
| Mean thickness of icy layers | cm |
| Mean fraction of icy layers of the total snow depth | 0-1 |
| Mean thickness of ground ice | cm |
| Mean hardness | N |
| Mean bottom layer hardness | N |
| Mean density | kg $m^{-3}$ |
| Mean thickness of layers with density > 350 kg $m^{-3}$ | cm |

*Calculations*

Parameters from both meteorological observations as well as from simulation outputs were listed in each winter (Table 1). From simulation outputs the average values of parameters were calculated for the whole winter period (November-April) and for three winter periods separately - early winter (November-December), mid-winter (January-February) and late winter (March-April). If snow fell later than 1 November or melted before 30 April, the average values for each parameter have been

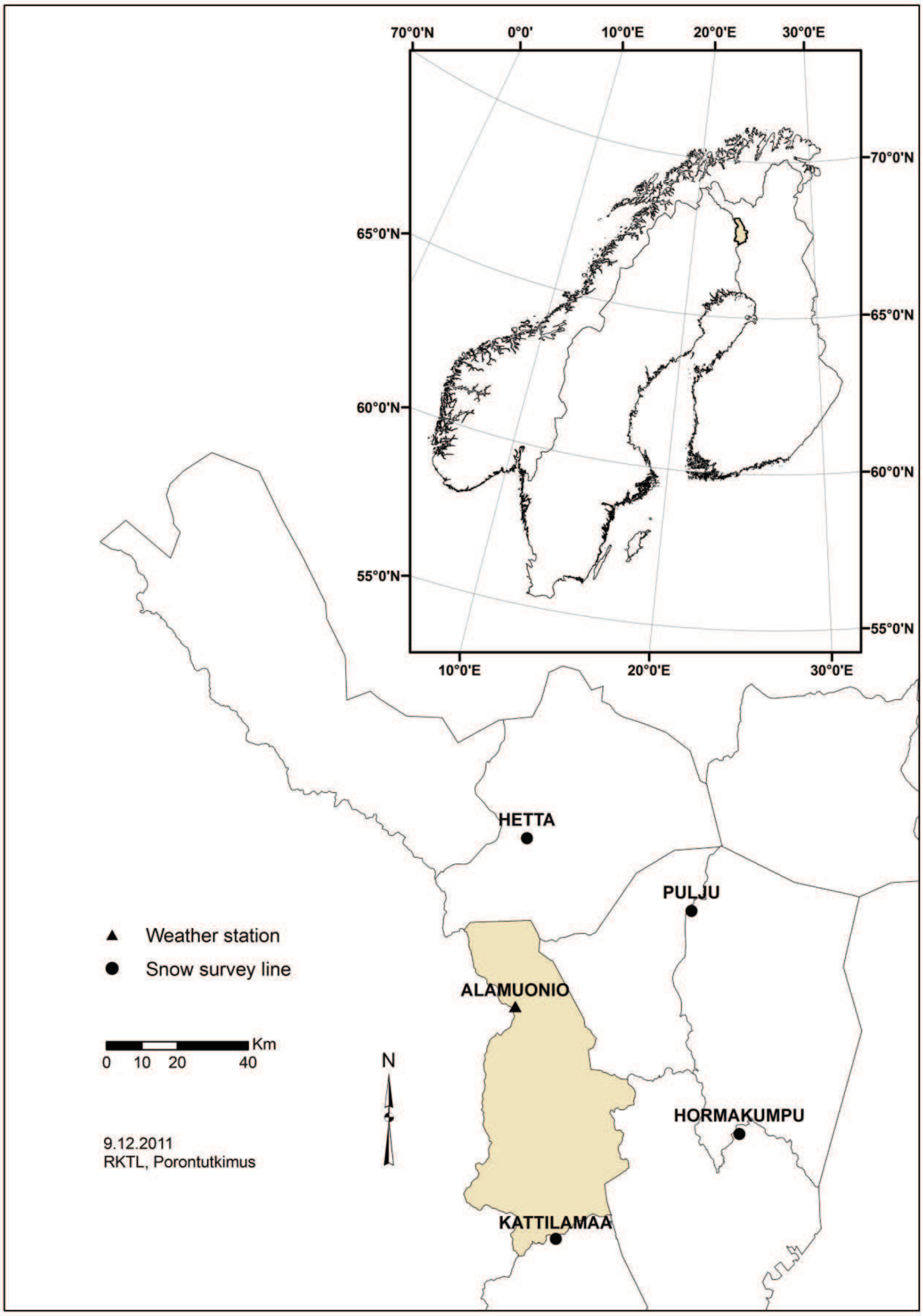


Figure 1. The reindeer management area and its 56 herding districts in northern Finland (the Muonio reindeer herding district shaded). Locations of the meteorological observation station operated by Finnish Meteorological Institute (FMI) in Alamuonio and the four Finnish Environment Institute's snow measurement lines (Hetta, Hormakumpu, Kattilamaa and Pulju) are marked on the map.

Table 2. Difficult snow conditions informed in the annual management reports of the Muonio reindeer herding district during 1972-2010. Calf production percentage (CPP), type of snow condition and reported impacts of snow conditions on reindeer populations (difficulties in grazing/active movement of reindeer/winter mortality) as well as responses of reindeer herding practices (feeding) are listed.

| | *CPP* | *Type of snow condition* | *Impacts / reactions* |
|---|---|---|---|
| 1972/1973 | 36.9 | Mold growth on pastures; Late melt | Winter mortality |
| 1976/1977 | 31.2 | Late melt | |
| 1979/1980 | 50.8 | Deep snow; Late melt | Difficulties in grazing |
| 1990/1991 | 48.7 | Deep snow | Difficulties in grazing |
| 1991/1992 | 52.4 | Snow to unfrozen ground; Ground ice | Difficulties in grazing; Active movement of reindeer; Winter mortality |
| 1992/1993 | 28.7 | Deep snow | Difficulties in grazing; Feeding; Winter mortality |
| 1993/1994 | 29.9 | Late melt | Difficulties in grazing |
| 1994/1995 | 49.0 | Deep snow; Late melt | Difficulties in grazing |
| 1995/1996 | 26.4 | Deep snow; Late melt | Difficulties in grazing; Winter mortality |
| 1996/1997 | 20.6 | Deep snow; Mold growth on pastures | Difficulties in grazing; Feeding |
| 1997/1998 | 49.6 | Deep snow | Difficulties in grazing; Feeding |
| 2004/2005 | 68.4 | Deep snow; Ice layers | Difficulties in grazing; Feeding |
| 2006/2007 | 56.5 | Deep snow; Ground ice | Difficulties in grazing; Feeding; Winter mortality |
| 2007/2008 | 54.3 | Deep snow; Late melt | Difficulties in grazing |
| 2008/2009 | 52.3 | Deep snow; Late melt | Difficulties in grazing; Feeding |
| 2009/2010 | 58.6 | Deep snow; Late melt; Ground ice | Difficulties in grazing; Feeding |

calculated for the snow covered period only. A layer was classified as icy if simulation indicated melt and refreeze of the layer, and either major or minor grain type of the layer was melt/refrozen grains. A bottom layer was classified as ground ice if both major and minor grain types were melt/refrozen grains, and layer had gone through melt and refreeze.

Statistical analysis of the reindeer and snow data was done using the Systat 13 and the IBM SPSS Statistics 20 softwares. Trends and statistical significance of the observed trends in reindeer and snow data were examined using the Mann-Kendall test. Pearson correlation test was conducted between the studied snow related parameters. The unpaired two sample t-test was used to determine the differences in snow parameters between the winters judged as difficult or easy according the reindeer herders. T-tests were done as two-tailed and assuming equal variance for the two samples. A principal component analysis (PCA) was made to extract the components accounting for most of the variance in our set of 14 observed or simulated snow related parameters. Extracted four principal components were included in the analyses of correlations and t-tests.

## Results

### *Snow characteristics relevant for reindeer herding*

#### Reindeer herders' experiences

The annual management reports of the Muonio herding district include, among other information, reindeer herders' experiences of snow con-

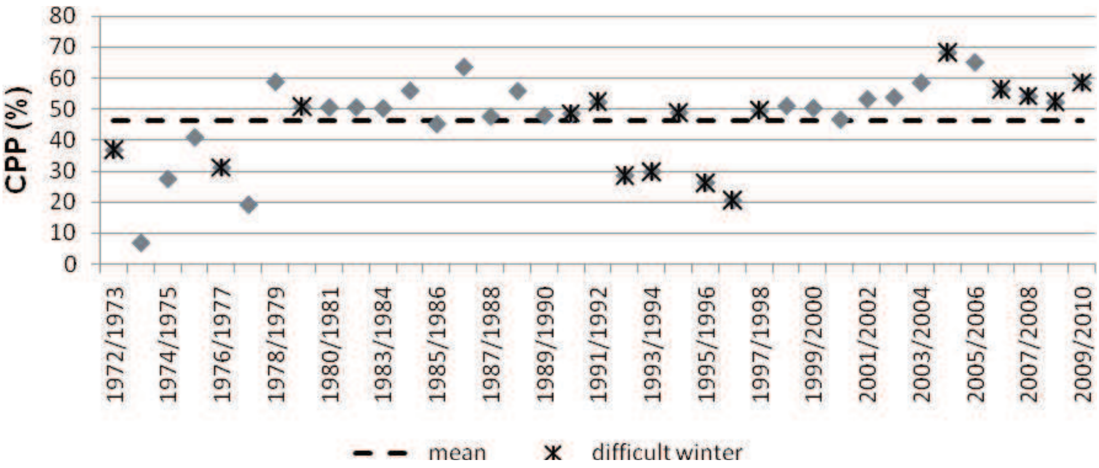


Figure 2. The annual and mean calf production percentage (CPP) in the Muonio reindeer herding district during 1972-2010. Winters experienced as difficult by the reindeer herders are marked with stars.

ditions during the winters and their response to difficult snow conditions. We had access to 38 reports between 1972/1973-2009/2010. Altogether 22 of the winters were classed as easy; in 16 winters snow conditions were experienced difficult (Table 2) and 12 of these cases were explained by deep snow cover. During nine of the winters snow melted late. In four winters, problems were caused by icy snow or ground ice (1991/1992, 2004/2005, 2006/2007 and 2009/2010). During three autumns the snow cover was reported to be formed on unfrozen ground, which means favorable conditions for mold growth and mold growth on pastures was reported during two of these winters. According the t-test, mean and maximum snow depth as well as, consequently, ground surface temperature were significantly higher ($p<0.001$) during the winters with reported difficult snow conditions; and snow season was significantly longer ($P$=0.02).

*Observed snow conditions and reindeer calf production*

Snow depth and length of snow cover time varied greatly among the winters (Table 3). No significant trends were observed in the long time series of these. Large between-year variability was seen also in calf production percentage during the observation period (Fig. 2). Weak but statistically significant increase in CPP of 0.483 per year was estimated using the Mann-Kendall test on trend in a time series ($P$=0.002).

Table 3. Mean, minimum, maximum and standard deviation of snow amount and duration parameters in Muonio during 1972/1973-2009/2010.

| | *Mean* | *Min* | *Max* | *St. Dev.* |
|---|---|---|---|---|
| Formation date | 24.10 | 3.10 | 27.11 | 12 days |
| Melt date | 14.5 | 28.4 | 1.6 | 8 days |
| Duration (days) | 202 | 166 | 229 | 16 |
| Max snow depth (cm) | 82 | 55 | 109 | 15 |

Relevance of snow depth and melt date, experienced by reindeer herders, was confirmed since CPP was negatively correlated to winter mean and maximum snow depth (R=-0.45; $P$=0.005 and -0.38; 0.02, respectively) and length of snow cover time (R=-0.37; $P$=0.02) (Fig. 3). Still, winters with reported difficult snow conditions did not clearly show in the time series of CPP (Fig. 2) and

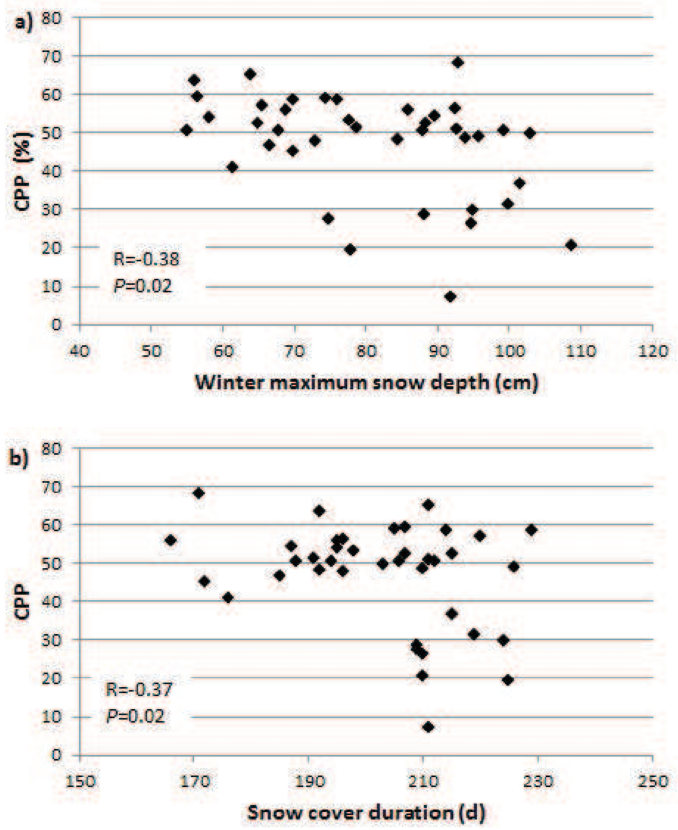


Figure 3. Calf production percentage (CPP) in relation to the annual observed maximum snow depth (a) and duration of the snow cover (b) in the Muonio reindeer herding district during 1972-2010. Pearson correlation coefficients and *P*-values given in the figures.

CPP between winters with easy and difficult snow conditions did no differ significantly from each other according the t-test.

*Validation of the model SNOWPACK*

Simulated values of mean monthly snow densities were compared to the monthly observations from the four survey lines of Finnish Environment Institute (Fig. 4). The densities simulated by the SNOWPACK were generally higher than the observed ones; however, inter-annual variation in snow density was well reproduced by the model. The Pearson correlation coefficients between the SNOWPACK model outputs and the snow survey observations ranged from 0.08 in Hormakumpu (*P*=0.745), 0.49 in Kattilamaa (*P*=0.002), 0.56 in Hetta (*P*=0.001) to 0.58 in Pulju (*P*=0.004). When mean value of these four surveys was compared

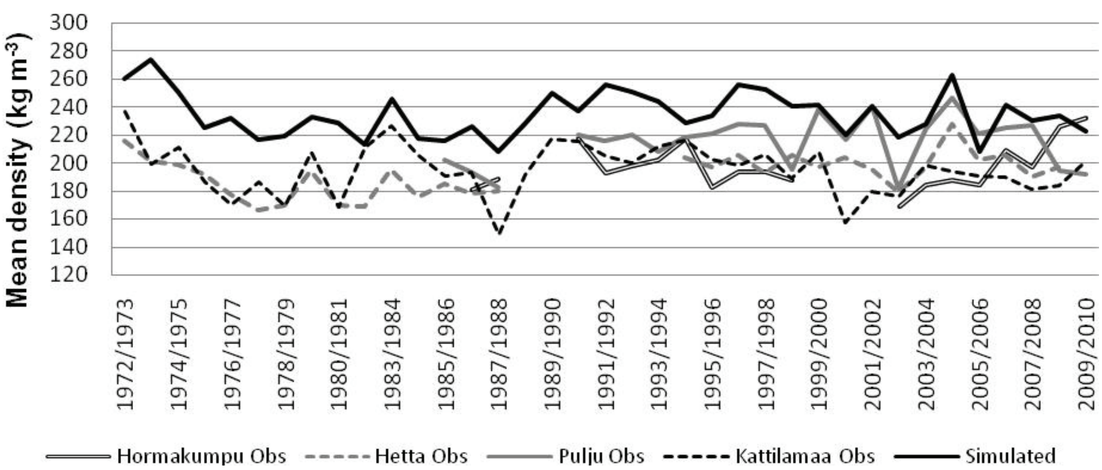


Figure 4. The mean snow density values (calculated from monthly values for whole winter) in open areas at four Finnish Environment Institute's snow measurement lines and in the SNOWPACK simulations for open area.

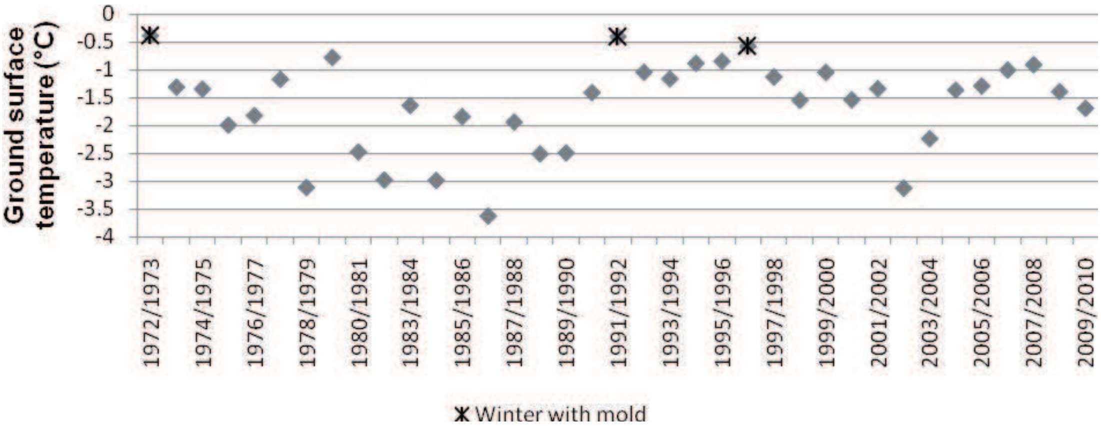


Figure 5. The mean simulated ground surface temperature for the whole snow cover period during 1972-2010. Three winters with conditions favoring mold growth reported by the reindeer herders marked with stars.

to the simulated one, correlation was highest (r=0.61; $P$<0.001).

*Distinguishing difficult winters for reindeer herding using snow structure simulations*

As observed snow parameters, simulated structural parameters showed considerable variation between the winters, with no significant trends seen in the long time series (Table 4). Simulated mean snow density was significantly higher ($P$=0.02) during the winters with reported difficult snow conditions. Relevance of snow structural parameters was confirmed as CPP was negatively correlated to winter mean snow density and mean thickness of layers with density > 350 kg m$^{-3}$ (R=-0.39; $P$=0.02 and -0.36; 0.03, respectively).

We used historical records in annual management reports to evaluate if the model was able to capture the problematic snow conditions for the herders. Snow covering unfrozen ground / mold growth on pastures were reported during autumns 1972, 1991 and 1996. Also Kumpula *et al.* (2000) observed exceptional growth of microfungi on pastures during winter 1996/1997. Simulated ground surface temperature was 0°C on the formation date of the permanent snow cover during two of these autumns, but this was the case also during additional eight autumns. When looking at the simulated mean ground surface temperature for the whole winter period, these three reported winters had clearly higher ground surface temperature than any other winters, equal or higher than -0.5 °C (Fig. 5).

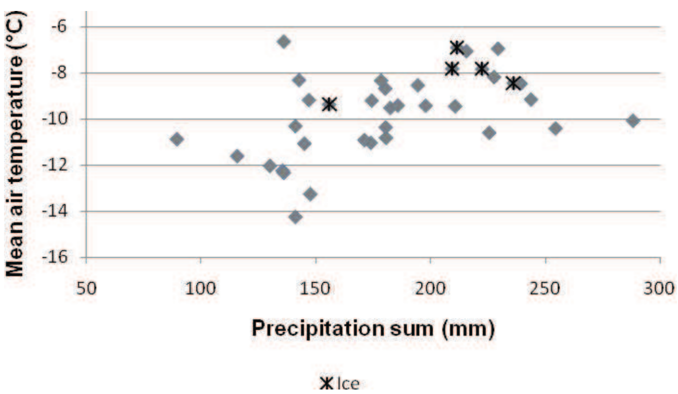


Figure 6. The measured annual mean air temperature during winter in relation to the corresponding mean precipitation sum in Muonio during 1972-2010. Winters with icy conditions reported by reindeer herders marked with stars.

Table 4. Mean, minimum, maximum and standard deviation of whole winter mean values of the selected snow structural parameters simulated by the SNOWPACK model in Muonio during 1972-2010.

| | *Mean* | *Min* | *Max* | *St. Dev.* |
|---|---|---|---|---|
| Thickness of icy layers (cm) | 8.3 | 0.9 | 21.3 | 5.6 |
| Fraction of icy layers | 0.16 | 0.01 | 0.31 | 0.09 |
| Mean hardness (N) | 251 | 101 | 379 | 78 |
| Mean density (kg $m^{-3}$) | 235 | 208 | 274 | 16 |
| Thickness of layers with density > 350 kg $m^{-3}$ (cm) | 1.5 | 0.0 | 8.0 | 2.1 |

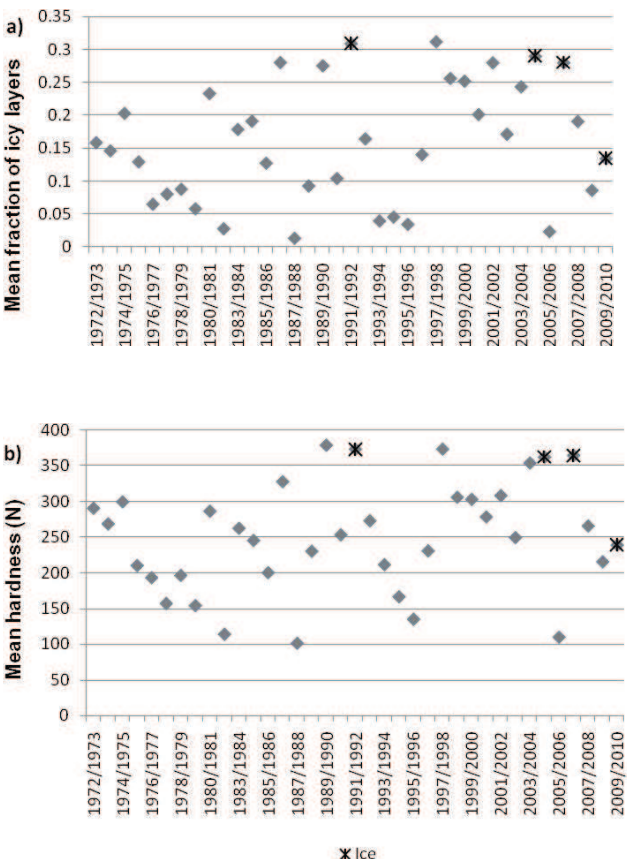


Figure 7. The simulated mean fraction of icy layers (a) and hardness of the snow cover (b) during winters 1972-2010. Winters with icy conditions reported by the reindeer herders marked with stars.

Icy snow and/or ground ice conditions were reported during four winters (1991/1992, 2004/2005, 2006/2007 and 2009/2010). These winters were not possible to distinguish accurately, when comparing winters on the basis of meteorological observations (Fig. 6). Three of the four winters with reported icy conditions had mean air temperatures as well as precipitation sums above the long term means, but in addition, ten other winters had this kind of conditions with no problems with icy snow reported.

Weather events leading to icy conditions were seen in the meteorological data only when looking at detailed three hour time resolution. During most of the events the air temperature stayed above zero at least for 24 hours, and maximum observed air temperature was several degrees above zero (3 - 6 °C). After the warm spell, temperature dropped within 24 hours clearly below freezing. Occurrence of rain was not necessary during these events, but in some cases rain on snow before the drop in the temperature led to thick icy layers.

When analyzing the mean values of the simulated snow structural parameters, only few proved useful for identifying the icy conditions. The highest quartile of simulated fractions of icy layers included three of the four winters with reported icy conditions - together with six winters with no icy conditions reported (Fig. 7a). Mean hardness of the snow cover (Fig. 7b) showed the similar result.

On the basis of graphical outputs we identified the winters with thick (> 10 cm) ground ice layer or exceptionally thick (> 20 cm) icy layer anywhere in the snow cover during the early and/or mid-winter. Three of the four winters with reported icy conditions could be distinguished using this method. For example during winter 1991/1992 the snow cover was not exceptionally deep but conditions were experienced as problematic. On the basis of the simulated snow structure evolution (Fig. 8) it is seen that a thick icy layer was formed in the snow cover in the end of January, and it was preserved till the spring. This layer probably prevented reindeer from grazing the ground lichen, and it did not help them to reach arboreal lichen either. For the 37-winters study period, simulation outputs showed icy conditions during five winters even if these were not reported by reindeer herders.

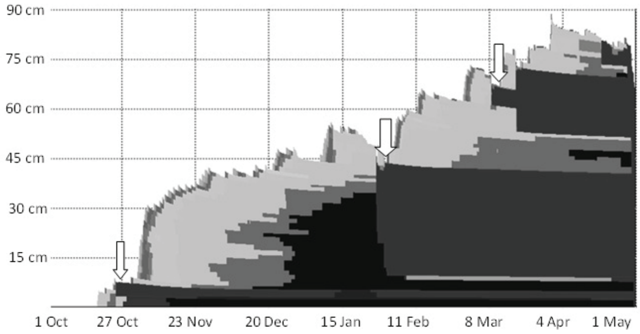


Figure 8. Evolution of the snow structure during winter 1991/1992 according to the simulations made by the SNOWPACK model. Shadowed areas separate the layers with different snow structure. Areas with light gray shading indicate dry snow with grains recently bonded together, and dark shaded areas closer to the bottom of the snow cover represent layers with loosely bonded, porous depth hoar. Occasions with melt and subsequent refreeze of snow (formation of icy layers or ground ice) are marked with white arrows. Icy layers formed during the early or mid-winter are possible to distinguish throughout the winter until the snow melts.

*Principal components of the snow parameters*

In PCA, observed and simulated snow parameters were reduced to four principal components, which explain approximately 80% of the total variance in the variables. In the further analysis these were called 'Snow amount' (PC1; *e.g.* snow depth and ground surface temperature; explains 33.27% of the total variance), 'Quality of snow' (PC2; *e.g.* snow hardness and thickness of ice layers; 23.19%), 'Ground ice' (PC3; thickness of ground ice, bottom layer hardness; 15.12%) and 'Duration of the snow season' (PC4; 8.88%). CPP was positively correlated with the Quality of snow-component ($R=0.47$; $P=0.003$), and in the t-test the Snow amount-component got significantly higher values during the winters experienced as difficult by reindeer herders compared to the easy winters ($P=0.003$). Quality of snow-component, in turn, got significantly lower values during the winters with difficult snow conditions ($P=0.005$).

## Discussion

We used combination of meteorological observations, snow structure simulations and reports by reindeer herders to study the relevance of snow properties on reindeer herding in Muonio reindeer herding district in northern Finland. Suitability and reliability of a snow structure model SNOWPACK was evaluated on the basis of the measured snow density observations and by comparing the simulated snow characteristics to annual reproduction rate by reindeer and to observations of herders concerning the snow conditions.

According the observations made by the reindeer herders in Muonio, deep snow cover and late snow melt are the most common unfavorable conditions for reindeer herding. Other problematic snow related conditions, are winters with icy snow or ground ice and snow cover that forms on unfrozen ground, potentially leading to mold growth. In previous studies, deep snow cover and late snow melt have been observed to cause high winter mortality (*e.g.* Kumpula & Colpaert, 2003; Helle & Kojola, 2008) and low calf production (*e.g.* Aanes *et al.,* 2000; Kumpula, 2001) of caribou and reindeer. Relevance of these snow characteristics for reproduction rate of reindeer was also observed in this work – reindeer calf production in the Muonio herding district decreased as maximum snow depth and length of snow cover time increased.

Effects of snow structure on reindeer and caribou populations are less extensively studied. Ground ice has been seen to limit Svalbard reindeer population growth rate or cause population crashes (Kohler & Aanes, 2004; Hansen *et al.,* 2011). Weather conditions favoring ice formation have been shown to be related to calf production and winter survival of reindeer (*e.g.* Kumpula & Colpaert, 2003; Helle & Kojola, 2004; 2008), but only small number of direct observations on ice formation has been made.

Our results confirm the view (Helle & Kojola, 2008; Vikhamar-Schuler *et al.,* 2013) that the icy conditions in snow or on ground are difficult to distinguish on the basis of long term meteorological observations. In our study the icy snow and/or ground ice conditions could be estimated with some accuracy using combination of winter mean air temperatures and precipitation sums, but this method informed also false cases relatively often (ten times during the 37 winter study period). Graphical results of the SNOWPACK simulations could be used to distinguish the icy conditions in three of four reported cases, but there were also five false cases during the study period. Simulated values of fraction of icy snow and mean snow hardness could also be used to detect the icy snow conditions. Ground ice reported in 2009/2010 could not be detected using any of these methods. Proportions of false alarms (ground ice simulated but not reported) and failed detections (ground ice reported but not simulated) were similar to those reported by Vikhamar-Schuler *et al.* (2013) in Kautokeino.

Even though some winters reported by the herders to have exceptional snow conditions (*e.g.* in 1972/1973 mold growth on pastures and late snow melt; in several winters during 1990s deep and/or icy snow cover) had also low reindeer calf production, these winters were not always clearly distinguished in the time series of CPP. Nevertheless, on the basis of the annual management reports winters experienced problematic led to changes in herding practices and caused more herding work and expenses for reindeer herders (*e.g.* in the form of supplementary winter feeding). Also losses due to predation were probably partly connected to difficult snow conditions (see Tveraa *et al.,* 2003).

Reindeer herding is relatively adaptable to intra- and inter-annual variations in grazing conditions (Tyler *et al.,* 2007; Roturier & Roue, 2009; Riseth *et al.,* 2010; Vuojala-Magga *et al.,* 2011). In the old intensive herding system the reindeer herders tried to find most suitable grazing areas for reindeer and also aided reindeer to make craters during winters with difficult snow conditions. Tightly herded animals could also be released to graze freely on arboreal lichen pastures (Helle & Jaakkola, 2008). Cutting old trees to provide reindeer arboreal lichens has also been done in the past (Berg *et al.,* 2011). Since the 1980s, supplementary feeding of reindeer has been carried out annually in Muonio reindeer herding district, and it has gradually become more common due to the reduction of the most important natural winter forage (ground and arboreal lichens). Reindeer are usually fed on pastures, certain part of herd is also gathered for feeding in pens.

Compared to Kautokeino region in northern Norway, where the model has been previously used to estimate the foraging conditions for reindeer, Muonio has considerably milder winter climate. Main difference still is the presence of the forest pastures, which complicates the conclusions drawn from the model outputs. In forested areas snow can affect foraging conditions positively by lifting the animal and giving better access to arboreal lichens (*Alectoria, Bryoria* ssp.) (Helle, 1984).

In addition to availability of winter forage, there are other factors affecting the well-being of the reindeer population. Poor body condition of animals in autumn due to foraging conditions and insect harassment in previous summer affect the successful preparation to winter (Holster, 1948; Helle, 1980; Dau, 2005). The annual reports of Muonio reindeer herding district listed also damages to reindeer by traffic and predation. These damages had large year-to-year variability and ranged between 79-446 individuals. This corresponded to 1-7 % of annual number of reindeer in winter stock, but did not have significant correlation with the CPP of the district.

SNOWPACK is not a spatial model, and simulations made with input data from a certain point best represent the mean snow conditions of the herding district. Pasture areas with variable vegetation and topography will develop variable snow covers. In the future, developing SNOWPACK model more suitable for forest landscape conditions or modeling snow distribution *e.g.* by a distributed model Alpine3D (Lehning *et al.,* 2006; Stähli *et al.,* 2009) are noteworthy options. Canopy module development should be continued in different types of forest environments, including different forest vegetation types and canopy coverages.

Using the structural modeling of annual snow conditions can give valuable information to reindeer herding compared to standard meteorological observations if present models are developed to be more suitable for northern boreal environment and also more precise forest and vegetation type data is used as simulation inputs. Even though the most often experienced problematic snow conditions (deep snow cover and late snow melt) are easily distinguished from the meteorological time series, use of this type of model improves the detection of icy snow or ground surface conditions. In our study, the winters which were reported to have conditions favorable for mold growth on pastures could be distinguished most reliably from the SNOWPACK outputs.

Climate change will lead to changes in the established winter weather patterns and snow conditions, to which large fraction of the arctic and boreal species are well adapted (ACIA, 2004; IPCC, 2007). The on-going and expected change will affect in many ways the foraging conditions for reindeer in winter, influencing the productivity and profitability of reindeer husbandry as a livelihood (Heggberget *et al.,* 2002; Post & Forchhammer, 2002; Tyler, 2010; Moen, 2008; Turunen *et al.,* 2009). Combination of climate and snow modeling can be a valuable tool when estimating the degree and range of these changes. In the future not only reindeer populations and reindeer husbandry, but also many other arctic and boreal species will be affected by changes in the length of the snow season, snow depth and frequency of the ground ice on vegetation.

**Acknowledgements**

We thank Reija Ruuhela, Asko Hutila and Henriikka Simola from Finnish Meteorological Institute for providing us the meteorological data needed in the snow modeling. We also thank Michael Lehning from the Swiss Federal Institute for Snow and Avalanche Research for helping us with the simulations made by the SNOWPACK model. We acknowledge the snow line data which was acquired by Heidi Sjöblom and Hannu Sirviö at Finnish Environmental Institute, SYKE. We thank Heikki Törmänen from Finnish Game and Fisheries Research Institute for technical assistance in the manuscript preparation. Taisto Ristimella and Aslak Kotakorva at the Muonio reindeer herding district and Anne Ollila and Sirpa Valkama at the Reindeer Herders' Association helped us to collect the local information on snow and foraging condition by reindeer, which we warmly acknowledge. Finnish Ministry of Agriculture and Forestry has supported our work financially. We are grateful to Dr. Carl Soulsbury for the valuable comments that have greatly improved the manuscript.

## References

**Aanes, R., Sæther, B.-E. & Øritsland, N. A.** 2000. Fluctuations of an introduced population of Svalbard reindeer: The effects of density dependence and climatic variation. – *Ecography* 23: 437-443.

**ACIA (Arctic Climate Impact Assessment).** 2004. 'Impacts of a warming climate: Final overview report.' (Cambridge University Press, Cambridge and New York.)

**Adamczewski, J. Z., Gates, C. C., Soutar, B. M. & Hudson, R. J.** 1988. Limiting effects of snow on seasonal habitat use and diets of caribou *(Rangifer tarandus groenlandicus)* on Coats Island, Northwest Territories. – *Canadian Journal of Zoology* 66: 1986-1996.

**Adams, L. G. & Dale, B. W.** 1998. Reproductive performance of female Alaskan caribou. – *Journal of Wildlife Management* 62: 1184-1195.

**Bartelt, P. & Lehning, M.** 2002. A physical SNOWPACK model for the Swiss avalanche warning: Part I. Numerical model. – *Cold Regions Science and Technology* 35: 123-145.

**Bavay, M., Lehning M., Jonas, T. & Löwe, H.** 2009. Simulations of future snow cover and discharge in Alpine headwater catchments. – *Hydrological Processes* 22, doi: 10.1002/hyp.7195.

**Berg, A., Josefsson, T. & Östlund, L.** 2011. Cutting of lichen trees: A survival strategy used before the 20th century in northern Sweden. – *Vegetation History and Archaeobotany* 20: 125-133.

**Dau, J.** 2005. Two caribou mortality events in Northwest Alaska: Possible causes and management implications. – *Rangifer Special Issue* 16: 37-50.

**Drebs, A., Nordlund, A., Karlsson, P., Helminen, J. & Rissanen,** P. 2002. Climatological statistics of Finland 1971-2000. Climate statistics of Finland No. 2002(1). Finnish Meteorological Institute, Helsinki.

**Fancy, S. G. & White, R. G.** 1985. Energy expenditures by caribou while cratering in snow. – *Journal of Wildlife Management* 49: 987-993.

**Hansen, B. B., Aanes, R., Herfindal, I., Kohler, J. & Saether, B. E.** 2011. Climate, icing, and wild arctic reindeer: Past relationships and future prospects. – *Ecology* 92: 1917-1923.

**Heggberget, T.M., Gaare, E. & Ball, J.P.** 2002. Reindeer *(Rangifer tarandus)* and climate change: Importance of winter forage. – *Rangifer* 22: 13-31.

**Helle, T.** 1980. Laiduntilanteen muutokset ja riskinotto porotaloudessa [Changes in the state of grazing areas and risk taking in Finnish reindeer management]. – *Lapin tutkimusseura: Vuosikirja* 21: 13-21. [In Finnish with English summary].

**Helle, T.** 1984. Foraging behaviour of semi-domesticated reindeer *(Rangifer tarandus tarandus)* in relation to snow in Finnish Lapland. – *Reports of Kevo Subarctic Research Station* 19: 35-47.

**Helle, T. & Tarvainen, L.** 1984. Determination of the winter digging period of semi-domestic reindeer in relation to snow conditions and food resources. – *Reports of Kevo Subarctic Research Station* 19: 49-56.

**Helle, T. & Kojola, I.** 2004. Porokantojen vaihtelut Fennoskandiassa – selitykset ja niiden arviointi. – *Suomen Riista* (50): 18-32.

**Helle, T. & Jaakkola, L.M.** 2008. Transition in herd management of semi-domesticated reindeer in northern Finland. – *Annales Zoologi Fennici* 45: 81-101.

**Helle, T. & Kojola, I.** 2008. Demographics in an alpine reindeer herd: Effects of density and winter weather. – *Ecography* 31: 221-230.

**Holleman, D. F., Luick, J. R. & White, R. G.** 1979. Lichen intake estimates for reindeer and caribou during winter. – *Journal of Wildlife Management* 43: 192-201.

**Holster, K.** 1948. Suopunginheittoja. – *Poromies* 1948 (2): 21-23.

**IPCC.** 2007. 'Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change.' [Ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller]. (Cambridge University Press, Cambridge and New York.)

**Kellomäki, S., Maajärvi, M., Strandman, H., Kilpeläinen, A. & Peltola, H.** 2010. Model computations on the climate change effects on snow cover, soil moisture and soil frost in the boreal conditions over Finland. – *Silva Fennica* 44: 213-233.

**Kohler, J. & Aanes, R.** 2004. Effect of winter snow and ground-icing on a Svalbard Reindeer population: Results of a simple snowpack model. – *Arctic, Antarctic and Alpine Research* 36: 333-341.

**Konzelmann, T., van de Wal, R.S.W., Greuell, W., Bintanja, R. Henneken, E.A.C. & Abe-Ouchi, A.** 1994. Parameterization of global and longwave incoming radiation for the Greenland ice sheet. – *Global and Planetary Change* 9: 143-164.

**Kumpula, J., Parikka, P. & Nieminen, M.** 2000. Occurrence of certain microfungi on reindeer pastures in northern Finland during winter 1996-97. – *Rangifer* 20: 3-8.

**Kumpula, J.** 2001. Winter grazing of reindeer in woodland lichen pasture – Effect of lichen availability on the condition of reindeer. – *Small Ruminant Research* 39: 121-130.

**Kumpula, J. & Colpaert, A.** 2003. Effects of weather and snow conditions on reproduction and survival of semi-domesticated reindeer *(R.t.tarandus)*. – *Polar Research* 22: 225-233.

**Kumpula, J., Lefrère, S. & Nieminen, M.** 2004. The use of woodland lichen pasture by reindeer in winter with easy snow conditions. – *Arctic* 57: 273-278.

**Kumpula, J., Tanskanen, A., Colpaert, A., Anttonen, M., Törmänen, H., Siitari, J. & Siitari, S.** 2009. Poronhoitoalueen pohjoisosan talvilaitumet vuosina 2005–2008: Laidunten tilan muutokset 1990-luvun puolivälin jälkeen. Riista- ja kalatalous: Tutkimuksia No. 3. Finnish Game and Fisheries Research Institute, Helsinki.

**Lee, S. E., Press, M. C., Lee, J. A. Ingold, T. & Kurttila, T.** 2000. Regional effects of climate change on reindeer: A case study of the Muotkatunturi region in Finnish Lapland. – *Polar Research* 19: 99-105.

**Lehning, M., Bartelt, P., Brown, B., Russi, T., Stöckli, U. & Zimmerli, M.** 1998. SNOWPACK model calculations for avalanche warning based upon a network of weather and snow stations. – *Cold Regions Science and Technology* 30: 145-157.

**Lehning, M., Bartelt, P., Brown, B., Fierz, C. & Satyawali, P.** 2002a. A physical SNOWPACK model for the Swiss avalanche warning. Part II. Snow microstructure. – *Cold Regions Science and Technology* 35: 147-167.

**Lehning, M., Bartelt, P., Brown, B. & Fierz, C.** 2002b. A physical SNOWPACK model for the Swiss avalanche warning service. Part III. Meteorological forcing, thin layer formation and evaluation. – *Cold Regions Science and Technology* 35: 169-184

**Lehning, M., Völksch, I., Gustafsson, D., Nguyen, T.A., Stähli, M. & Zappa, M.** 2006. ALPINE3D: A detailed model of mountain surface processes and its application to snow hydrology. – *Hydrological Processes* 20: 2111-2128.

**Lehning, M. & Fierz, C.** 2008. Assessment of snow transport in avalanche terrain. – *Cold Regions Science and Technology* 51: 240-252.

**Lundy, C., Brown, R.L., Adams, E.E., Birkeland, K.W. & Lehning, M.** 2001. A statistical validation of the SNOWPACK model in a Montana climate. – *Cold Regions Science and Technology* 33: 237-246.

**Moen, J.** 2008. Climate change: Effects on the ecological basis for reindeer husbandry in Sweden. – *Ambio* 37: 304-311.

**Perälä, J. & Reuna, M.** 1990. Lumen vesiarvon alueellinen ja ajallinen vaihtelu Suomessa. Publications of Water and Environment Research Institute No. A 56. Water and Environment Research Institute, Helsinki.

**Post, E. & Stenseth, N.C.** 1999. Climate change, plant phenology, and northern ungulates. – *Ecology* 80: 1322-1339.

**Post, E. & Forchhammer, M.** 2002. Synchronization of animal population dynamics by large-scale climate. – *Nature* 420: 168-171.

**Rasmus, S., Räisänen, J. & Lehning, M.** 2004. Estimating snow conditions in Finland in the late 21st century using the SNOWPACK-model with regional climate scenario data as input. – *Annals of Glaciology* 38: 238-244.

**Rasmus, S., Grönholm, T., Lehning, M., Rasmus, K. & Kulmala, M.** 2007. Validation of the SNOWPACK-model in five different snow zones in Finland. – *Boreal Environmental Research* 12: 467-488.

**Rasmus, S., Gustafsson, D., Koivusalo, H., Laurén, A., Grelle, A., Kauppinen, O.-K., Langvall, O., Lindroth, A., Rasmus, K., Svensson, M. & Weslien, P.** 2012. Estimation of winter leaf area index and sky view fraction for snow modelling in boreal coniferous forests – Consequences on snow mass and energy balance. – Hydrological Processes, doi: 10.1002/hyp.9432.

**Riseth J. Å., Tommervik H., Helander-Renvall E., Labba N., Johansson C., Malnes E., Bjerke J. W., Jonsson C., Pohjola V., Sarri L.-E., Schanche A. & Callaghan T.V.** 2010. Sami traditional ecological knowledge as a guide to science: snow, ice and reindeer pasture facing climate change. – *Polar Record,* doi:10.1017/S0032247410000434.

**Roturier, S. & Roue, M.** 2009. Of forest, snow and lichen: Sami reindeer herder's knowledge of winter pastures in northern Sweden. – *Forest Ecology and Management* 258: 1960-1967.

**Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L.P., Jones, C., Meier, M., Samuelsson, P. & Willén, U.** 2003. GCM driven simulations of recent and future climate with the Rossby Centre coupled atmosphere Baltic Sea regional climate model RCAO. Reports Meteorology and Climatology No. 101, SMHI, Norrköping.

**Skogland, T.** 1978. Characteristics of the snow cover and its relationship to wild mountain reindeer (*Rangifer tarandus tarandus* L.) feeding strategies. – *Arctic and Alpine Research* 10: 569-580.

**Solantie, R., Drebs, A., Hellsten, E. & Saurio, P.** 1996. Lumipeitteen tulo-, lähtö- ja kestoajoista Suomessa talvina 1960/61-1992/1993. Meteorologisia julkaisuja No. 34. Finnish Meteorological Institute, Helsinki.

**Solberg, E. J., Jordhøy, P., Strand, O.,. Aanes, R., Loison, A., Sæther, B.-E. & Linnell, J.D.C.** 2001. Effects of density-dependence and climate on the dynamics of a Svalbard reindeer population. – *Ecography* 24: 441-451.

**Stähli, M., Jonas, T. & Gustafsson, D.** 2009. The role of snow interception in wintertime radiation processes of a coniferous sub-alpine forest. – *Hydrological Processes* 23: 2498-2512.

**Telfer, E.S. & Kelsall, J.P.** 1984. Adaptation of some large north American mammals for survival in snow. – *Ecology* 65: 1828-1834.

**Turunen, M., Soppela, P., Kinnunen, H.,**

**Sutinen, M.-L. & Martz, F.** 2009. Does climate change influence the availability and quality of reindeer forage plants? – *Polar Biology* 32: 813-832.

**Tveraa, T., Fauchald, P., Henaug, C. & Yoccoz, N.G.** 2003. An examination of a compensatory relationship between food limitation and predation in semi-domisticated reindeer. – *Oecologia* 137: 370-376.

**Tyler, N., Turi, J., Sundset, M., Strøm Bull, K. Sara, M., Reinert, E., Oskal, N., Nellemann, C., McCarthy, J., Mathiesen, S., Martello, M., Magga, O., Hovelsrud, G., Hanssen-Bauer, I., Eira, N., Eira, I. & Corell, R.** 2007. Saami reindeer pastoralism under climate change: Applying a generalized framework for vulnerability studies to a sub-arctic social–ecological system. – *Global Environmental Change* 17: 191-206.

**Tyler, N J.C.** 2010. Climate, snow, ice, crashes, and declines in populations of reindeer and caribou (*Rangifer tarandus* L.). – *Ecological Monographs* 80: 197-219.

**Venäläinen, A., Tuomenvirta, H., Heikinheimo, M., Kellomäki, S., Peltola, H., Strandman, H. & Väisänen, H.** 2001. Impact of climate change on soil frost under snow cover in a forested landscape. – *Climate Research* 17: 63-72.

**Vikhamar-Schuler, D., Hanssen-Bauer, I., Schuler, T.V., Mathiesen, S.D. & Lehning, M.** 2013. Use of a multi-layer snow model to assess grazing conditions for reindeer. – *Annals of Glaciology* 54 (62): 214-226.

**Vuojala-Magga T., Turunen M., Ryyppö T. & Tennberg M.** 2011. Resonance strategies of Sami reindeer herding during climatically extreme years in northernmost Finland in 1970-2007. – *Arctic* 64: 227-241.

*Manuscript submitted 2 October 2013*
*revision accepted 10 February 2014*

Onko lumipeitteen rakenteen mallilla mahdollista arvioida poronhoidolle merkityksellisiä lumen ominaisuuksia?

*Summary in Finnish/Tiivistelmä:* Lumi vaikuttaa porojen laidunnusolosuhteisiin esimerkiksi lisäämällä liikkumisen ja kaivamisen energiankulutusta tai helpottamalla luppojäkälän saatavuutta. Tutkimuksia lumen rakenteen vaikutuksista porojen populaatiodynamiikkaan tai poronhoitoon on kuitenkin tehty vähän. Tutkimuksemme tavoitteena oli selvittää mitkä lumen ominaisuudet ovat poronhoitajien kokemusten mukaan merkityksellisiä poroille pohjoisboreaalisella vyöhykkeellä, ja vaikuttavatko nämä myös alueen porojen lisääntymismenestykseen.

Tavoitteenamme oli myös tutkia kykeneekö lumen rakenteen SNOWPACK-malli luotettavasti arvioimaan nämä lumen ominaisuudet. Yhdistimme työssämme Muonion paliskunnassa, pohjoisessa Suomessa, tehtyjä meteorologisia havaintoja ja lumen rakenteen simulointeja sekä paliskunnan poronhoitajien vuosiraportteja vuosilta 1972-2010.

Syvä lumi ja myöhäinen lumen sulaminen olivat yleisimmät raportoidut epäsuotuisat lumiolot. Lumen rakenteeseen liittyneet vaikeat olot tarkoittivat jäisiä lumikerroksia, maajäätä tai sulaa maata lumipeitteen alla, joka johti homeiden kasvuun laitumilla. Havaitsimme käänteisen riippuvuuden vasaprosentin sekä talven suurimman lumensyvyyden, lumipeiteajan keston ja lumen tiheyden välillä. SNOWPACK –malli kykenee suhteellisen luotettavasti arvioimaan poroille merkityksellisiä lumen rakenteellisia ominaisuuksia. Mallisimulaatioiden avulla erotimme kolme neljästä sellaisesta talvesta, joina poronhoitajat raportoivat vaikeista lumiolosuhteista jäisen lumen tai maajään vuoksi. Pystyimme myös luotettavasti erottamaan talvet, joiden olosuhteet mahdollistivat homeiden kasvun laitumille. Lumen rakenteen malli voi antaa arvokasta tietoa laidunnusolosuhteista, etenkin kun tarkastellaan lämpenevien talvien mahdollisia vaikutuksia poropopulaatioihin ja poronhoitoon elinkeinona.